Optical Spectra of Small-scale Sprite Features Observed at 10,000 fps

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November 22, 2022

Abstract

Spectra of small-scale sprite structures, downward and upward propagating streamers, glow, and beads, were recorded with a slit-less spectrograph at 10,000 frames per second (fps) from aircraft missions in 2009 and 2013. The spectra are dominated by emissions from molecular nitrogen, the 1 positive band in the red, and in the blue the 2 positive band plus the 1 negative band of molecular nitrogen ions. The excitation threshold for the blue emissions is higher than for the red emissions so the blue/red ratio can, in principle, be used as a proxy for the electron energy leading to the emissions. We extracted for analysis time series of spectra from 11 sprites: 18 time series from downwards propagating streamers, 6 from upward propagating streamers, 14 from glow and 12 from beads. The total number of spectra in the 50 time series is 953. Blue emissions are almost exclusively associated with streamers indicating the more energetic nature of streamers compared with glow and beads. Both downward and upward propagating streamers start and end with low blue emissions indicating time variations in the associated processes. Because the red and blue nitrogen emissions are significantly affected by quenching, which is altitude dependent, and we do not have sufficiently accurate altitudes, the observed spectral blue/red ratios cannot be directly applied to sprite models.

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Key Points:

- Spectra of small scale sprite features (downward and upward streamers, beads and glow) have been recorded at 10,000 spectra per second.
- The spectra are dominated by molecular nitrogen emissions. The relative blue and red emission rates can be used to assess the processes leading to the emissions.
- Blue emissions are almost exclusively associated with sprite streamers indicating more energetic processes compared to those associated with beads and glow.

Abstract

Spectra of small-scale sprite structures, downward and upward propagating streamers, glow, and beads, were recorded with a slit-less spectrograph at 10,000 frames per second (fps) from aircraft missions in 2009 and 2013. The spectra are dominated by emissions from molecular nitrogen, the 1st positive band in the red, and in the blue the 2nd positive band plus the 1st negative band of molecular nitrogen ions. The excitation threshold for the blue emissions is higher than for the red emissions so the blue/red ratio can, in principle, be used as a proxy for the electron energy leading to the emissions. We extracted for analysis time series of spectra from 11 sprites: 18 time series from downwards propagating streamers, 6 from upward propagating streamers, 14 from glow and 12 from beads. The total number of spectra in the 50 time series is 953. Blue emissions are almost exclusively associated with streamers indicating the more energetic nature of streamers compared with glow and beads. Both downward and upward propagating streamers start and end with low blue emissions indicating time variations in the associated processes. Because the red and blue nitrogen emissions are significantly affected by quenching, which is altitude dependent, and we do not have sufficiently accurate altitudes, the observed spectral blue/red ratios cannot be directly applied to sprite models.

1 Introduction

Optical spectra of sprites, first obtained by Mende et al. (1995); Hampton et al. (1996), are dominated by molecular nitrogen band emissions: The First Positive band system (1PN2) in the red and in the blue the Second Positive band system (2PN2) and the first Negative band system of molecular nitrogen ions (1NN2+). The excitation threshold for the first and second positive system is 7.4 eV and 11.0 eV, respectively, while ionization requires 15.6 eV (Cartwright, 1978; Vallance Jones, 1974). The emissions are very bright and they are readily identifiable in spectra recorded at 10,000 frames per second (Kanmae et al., 2010a), and therefore may be used to evaluate the temporal development of the characteristic energy of the electrons leading to the emissions.

The use of spectral features to evaluate the causal processes is not new. Suszcynsky et al. (1998) and Armstrong et al. (2000) compared emissions in the 380-450 nm region (blue), to emissions in the 600-900 nm region (red) and suggested that there are two separate mechanisms associated with the sprite emissions: An initial energetic process followed by less energetic processes. The observations were made from aircraft using photometers together with 30 fps video cameras. Morrill et al. (2002), also using aircraft data, found that emissions in sprite streamers indicate higher electron energies at lower altitudes. Similarly, Kuo et al. (2005) and Liu et al., (2006 and 2009a) used data from a spectrophotometer onboard the FORMOSAT-2 satellite to derive the characteristic electron energies and associated ambient electric fields. More recently, Gordillo-Vázquez et al. (2018) used sprite spectra with 0.24 nm resolution to derive mesospheric temperatures and found no measurable heating of the neutral atmosphere. Finally, modeling by Pérez-Invernón et al. (2018) indicate that the ratio of 1PN2 to 2PN2, the emissions that dominate the 10,000 frames per second observations presented in this paper, does not vary much for reduced electric fields above ~200 Td, but is adequate at lower fields. They suggest that a better ratio might be 1PN2 or 2PN2 to 1NN2+.

Sprites develop on millisecond time scales, and they have complex spatial structures with scale sizes down to a few 10s of meters. This obviously places severe limitations on observations made with traditional photometers and 30 fps video cameras. Fortunately, sprites are very bright, and therefore most of these limitations were overcome once high-speed imaging became available. Using high-speed imaging it is possible to observe sprites with sufficient temporal and spatial resolution to document details of sprite morphology (e.g. Stanley et al., 1999; Stenbaek-Nielsen et al., 2000; Cummer et al., 2006; McHarg et al., 2007; Stenbaek-Nielsen & McHarg, 2008; Stenbaek-Nielsen et al., 2013).

Sprite spectra with 3 ms temporal resolution were recorded in 2005 with a slit spectrograph (Kanmae et al., 2007). During the same 2005 campaign images were also recorded at 10,000 fps (0.1 ms temporal resolution). The images showed that sprite streamers are fast moving, small-scale, but very bright, features (Stenbaek-Nielsen et al., 2007). This makes them well suited for slit-less spectroscopy, and in 2009 sprite spectra using this technique were recorded at 10,000 fps (Kanmae et al., 2010a). While the slit-less spectra have less spectral resolution than those recorded with the slit spectrograph, spectra can be recorded within a much larger field of view, and spectra can be obtained of streamers as they propagate across the field of view. This will allow an investigation of temporal changes to the spectra.

Both the 2005 and the 2007 observations were made from the ground. Contrary to expectations, no blue emissions were detected, and it was suggested that the reason was absorption and scattering in the lower atmosphere. The 2009 spectra were recorded from an aircraft at high altitude, and, indeed, emissions in the blue were detected. Evaluating these observations Kanmae et al. (2010b) showed the more energetic nature of streamers compared to glows. A second similar aircraft mission was conducted in 2013.

There are many dynamic and bright small-scale features in sprites which are ideally suited for high-speed slit-less spectroscopy, and in this paper we present an analysis of spectra obtained at 10,000 fps in the 2009 and 2013 aircraft sprite missions. We evaluate nitrogen emissions in the blue and red from 4 sprite features: downward and upward propagating streamers, sprite glow, and beads. Streamers are mainly observed in the initial phase of a sprite event while glow and beads are longer lasting and largely stationary. Glow and beads are typically the main sprite features in video recordings (30 or 25 fps).

The spectra are dominated by molecular nitrogen emissions. Most of the spectra have a well-defined spectral signature between 625 and 700 nm in the red. This is the $\Delta\nu$=3 bands in the 1st positive system of molecular nitrogen. While they are generally less bright than the $\Delta\nu$=2 bands in the 720-780 nm range, they are better defined in our data, and we use them as primary selection criterion when selecting events. The wavelength range used for the blue emissions is 380-450 nm, which covers part of the 2P system of molecular nitrogen and molecular nitrogen ions. The 380 nm limit is the spectrograph low wavelength cut-off, and therefore only the longer wavelength bands of the 2P system will be detected. The spectrograph does not have enough resolution to fully separate 2PN2 and molecular nitrogen ion emissions, but since both require higher energies to emit than the 1PN2 band, alone the presence of blue in the spectra will indicate a more energetic process.

The nitrogen emissions are affected by quenching (deactivation of the excited molecules by atmospheric collisions rather than through photon emissions). Hence, if the observed emissions are to be used with models to infer the characteristic electron energies involved, which would be an obvious next step, the emissions have to be corrected for quenching. Quenching is altitude dependent, and there is unfortunately a substantial uncertainty on the altitudes of the emitting sprite features which, in effect, prevents the observations to be used quantitatively with models to infer the characteristic electron energies involved. We discuss this in detail in sections 4.1 and 4.2 below. Nevertheless, the ratio of blue to red emissions derived from our observed spectra is a convenient parameter for an evaluation of systematic differences between the 4 small-scale sprite features. In section 4.3 we present ratio averages across the entire data set, and in section 4.4 temporal changes observed within individual spectral time series.

2 Instrumentation

Essentially the same slit-less spectrograph was used in the 2009 and 2013 recordings at 10,000 fps. It was configured with a 100 lines/mm transmission grating blazed at 425 nm in front of a Nikon 50 mm f/1.4 lens on a Video Scope VS4-1845HS image intensifier. The extended blue response intensifier has a P24 phosphor (10 μs decay) preventing persistence onto following images. The intensified spectral image is relayed to the CMOS chip of a Vision Research Phantom high-speed camera. The Phantom camera uses GPS time, and it is configured and controlled by a laptop computer which is also used for the storage of events initially recorded in camera memory.

In 2009 we used a Phantom v7.1, which has 12 bit images, and in 2013 an improved Phantom v7.3 with 14 bit images. Both models use the same 800x600 pixel format CMOS chip, but at 10,000 fps hardware limitations reduce the usable image size. For the v7.1 (2009) we configured the Phantoms to 640x256 and for the v7.3 (2013) to 640x320 pixel image formats, corresponding to a field of view of 15x6 and 15x7.5 degrees respectively.

The spectrograph was mounted on an adjustable azimuth-elevation mount looking out through one of the left side windows on the aircraft. Co-mounted with the spectrograph we had a low light-level video camera (Watec 902H) to provide scene awareness and to record star background critical for accurate pointing information. On a separate mount, looking through another window, we had a second Phantom camera configured as an imager and a co-mounted Watec video camera, but these data were not used directly in the analysis presented here.

The spectrograph was wavelength calibrated using an Ocean Optics HG-1 Mercury Argon Calibration Source. The dispersion is 4.05 nm/pixel, and it varies only slightly across the field of view. During the missions we recorded spectra of a number of bright stars with known spectra. Analysis of the 2009 spectra shows a response across the visible and near-IR from 380 to 900 nm with a steep fall off in the blue and a peak response around 550 nm (Kanmae et al., 2010b). In the 2013 mission we looked through a quartz window expecting better response in the blue, but that was not the case, and we found the blue cut-off is primarily due to the transmission characteristics of the Nikon 50 mm lens. While the blue response in the 2013 mission was slightly better we did not find in the analysis any material differences between the spectra from the 2009 and the 2013 missions.

Most of the molecular nitrogen 2P bands emits at shorter wavelengths than the 380 nm instrument cut-off, which is unfortunate. On the other hand, the 2P bands are bright, and the cut-off prevents 2^{nd} order spectra to interfere with the 1^{st} order spectra which simplifies analysis considerably.

Getting the spectral information with slit-less spectroscopy requires small sources, ideally, as in astronomy, point sources. In that case the resolution would be 4.05 nm/pixel. While the sprite structures analyzed here are small, they are not point sources and the spectral resolution would be less. The structures are typically 3 to 10 pixels wide and the resolution would then be ~15-40 nm. This is not sufficient for a clear separation of the neutral and ion emissions in the blue, but acceptable when we just want to isolate the signals in the wavelength regions of the 1PN2 and 2PN2 bands.

With the 100 lines/mm grating first order spectra covering 0 to 800 nm are ~200 pixels wide, which is ~1/3 of the 640 pixel image width. On one of the flights in 2009 we used a 200 lines/mm grating to provide twice the spectral resolution, but the wider spectra (in pixels) significantly reduces the area in the image from which spectra can be recorded, and it resulted in an unacceptable loss of otherwise usable events.

3 Data

Sprites and their spectra were recorded at 10,000 fps in the 2009 and 2013 aircraft missions over the US mid-west region. Additionally, we recorded GPS aircraft position with 1 s temporal resolution, and lightning strikes from the National Lightning Detection Network (NLDN). A total of 60 sprites with spectra were recorded, but because of overlap of spectral features within an image, only relatively few events will produce spectra where the 1P (red) and 2P (blue) bands from particular sprite features are sufficiently isolated to allow evaluation. Only 2 of the 60 events were found to have all 4 sprite features, downward and upward propagating streamers, beads, and glow, present with spectra of sufficient quality for evaluation. However, there were a number of events with good spectra for 2 and 3 features thus allowing for a more statistical analysis.

For analysis we selected 11 events. An event was selected if it has usable spectra for at least 2 of the 4 sprite features in the analysis. The $\Delta\nu$=3 band of the 1P system of molecular nitrogen is typically a well-defined feature in the spectra. It is observed between 625-700 nm, and we used that spectral feature as primary selection criteria. For each feature within an event we then extracted as many sequential spectra as possible to provide data for an evaluation of the temporal development of the blue and red emissions. The 11 events yielded 50 sequences of spectra, 18 of downward streamers, 6 of upward streamers, 14 of glows, and 12 of beads. The total number of spectra in the 50 sprite feature sequences is 953.

Most of the spectra were present against a dark background, but there were some where otherwise well-defined spectral features were observed against a relatively uniform background created, for example, by the presence of a sprite halo. In this case we used background subtraction to isolate the spectral features of interest.

The spectra are affected by the atmosphere and by noise originating primarily in the camera intensifier. To evaluate this we analyzed spectra from the planet Jupiter which was in the field of view in a sprite recorded on 27 August 2009 at 091523 UT. We extracted 200 consecutive spectra, 0.02 s of data, and assuming that the emissions from Jupiter do not vary over the 0.02 s data sequence, the scatter in the brightness, which appears to be random, will reflect the uncertainty thus introduced on the data. To be consistent with the analysis presented in this paper, we evaluated the scatter for the same spectral bands, 380-450 nm in the blue and 625-700 nm in the red, used for the data analysis presented in this paper. Details of the procedure are given in section 4 below. The standard deviation in the red is 793 on a ~10,000 signal (8%) and for the blue 856 on a ~5,000 signal (19%). Following standard error analysis procedures (Taylor, 1997), we will use the Jupiter data to estimate error bars on temporal variations in spectra from individual sprites presented in section 4.4 below.

4 Analysis

Figure 1 shows an example of each of the analyzed features: Downward and upward propagating streamers, glow, and bead. Each of the 4 sections in the figure has to the left a 281x256 pixel (6.7x6.1 degrees field of view) sub-image extracted from the original image, and to the right the derived spectrum. The location of the sprite feature (the zero order spectrum) is given by the white vertical lines at top and bottom of each image. The feature and associated spectrum is bracketed by two white dashed horizontal lines which define the section of the columns over which we integrated to get the spectral signal. The number of pixels in the section, typically between 3 and 6, was set individually for each sequence to optimize the quality of the derived spectra. (The horizontal lines also have a small slant to compensate for the grating not being exactly aligned with the rows in the spectrograph CCD). The first order spectrum is seen toward the right in the sub-image. The second order spectrum would be located farther to the right and outside the sub-image, but is rarely detected. In the panel to the right of the image we show the spectrum derived by summing image pixel values in each image column between the two horizontal lines. The spectrum is wavelength scaled using 4.05 nm/pixel, as derived from a wavelength calibration, and the location of the zero order spectrum as origin. To allow easy visual comparison between individual spectra within a sequence and between sequences, we scaled all spectra to a fixed amplitude of the Δv=3 bands of the 1P system of molecular nitrogen. The blue section covers the wavelength range 380-450 nm and is shown in blue. The red section, 625-700 nm, is shown in red.

In the 4 examples presented in figure 1 we note that blue emissions, indicating a more energetic process, are only prominent in streamer spectra (upper row of figure 1). This is generally true for the entire data set analyzed. The downward and upward streamer examples in Figure 1 are from the same event (same image used in the figure). However, when comparing the two spectra, or any set of spectra from other events, quenching, which is altitude dependent, must be considered.

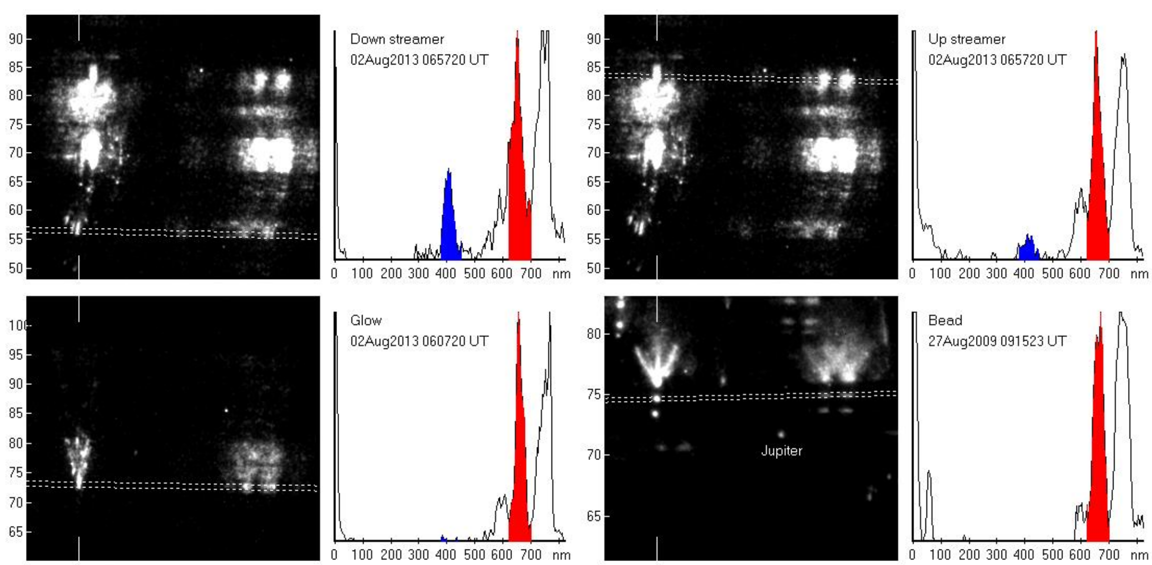

Figure 1. Examples of spectra: Downward and upward propagating streamers, glow, and bead. Note the example of downward and upward propagating streamers are from the same event. The spectra are normalized to the Δv=3 band of the 1P system in the red to allow easy visual

comparison with the more energetic 2P system and the 1NN2+ emissions in the blue. Note Jupiter in the field of view of the sprite in the lower right panel.

4.1 Uncertainty on altitude

The altitude of the emitting sprite feature is typically calculated from the elevation angle of the feature together with the range to the sprite. The high-speed camera had a co-aligned low-light-level video camera which provides good star fields from which the elevation angle to the sprite feature can be accurately determined, and the range is given by assuming that the sprite is at the same distance from the aircraft as the causal lightning strike recorded by NLDN.

The assumption of the sprite located at the same range as the lightning strike is very common and often, by necessity, made when observations are only available from a single site, as is the case here. However, this may lead to significant errors. We know that sprites can be many 10s of km from the lightning strike. Often, as in multiple C-sprite events, many sprites appear across the camera field of view clearly indicating onset of individual sprites across a large area. Sato et al. (2016) report sprites 8-20 km from the strikes based on observations from the International Space Station, and Yang et al. (2015) report on a sprite more than 38 km from the strike. Sao Sabbas et al. (2003) compared 40 triangulated sprite locations to their causal lightning strike and found a mean distance of 40 km; the maximum distance was 82 km. Wescott et al. (2001) presented one example where the sprite halo was centered essentially over the lightning location, but the sprites occurred ~20 km from the strike; other triangulated sprite locations in that study were up to 50 km from the associated strike. Finally, Lyons (1996) reported sprite locations up to 111 km from the strike. Most of the sprites in the data set analyzed here were observed at elevation angles between 10 and 20 degrees, and a change of 40 km in range, the mean distance between strike and sprite reported by Sao Sabbas et al. (2003), at an elevation angle of 15 degrees would change the altitude by 12 km. This is more than one atmospheric scale height which would significantly affect quenching.

4.2 Effect of quenching

Excited nitrogen molecules, neutrals and ions, may be deactivated (quenched) by atmospheric collisions before they emit. This process becomes increasingly important at lower altitudes. Armstrong et al. (1998), their figure 9, shows graphically the altitude effect of quenching on the photon yield: 1P2N has a yield of 80% at 80 km decreasing to 20% at 60 km; 2PN2 is 80% at 45 km and 20% at 25 km; 1NN2+ is 80% at 60 km decreasing to 20% at 40 km. Thus at sprite altitudes, 60-90 km, the main impact comes from quenching of the 1PN2 band system emitting in the red. All other being equal, the blue emissions should become increasingly prominent with lower altitude.

The altitude dependent increase in the observed blue/red (2PN2/1PN2) ratio due to quenching is shown in Figure 2. The quenching ratio has been calculated using the MSIS-E-90 model atmosphere with newer emission and quenching rates given by Ihaddadene and Celestin (2016).

The effect on optical sprite observations is clearly illustrated in the image inserted in Figure 2. The image is from the first color video recording obtained by a University of Alaska TV camera built for auroral research (Sentman et al., 1995). While the top of the sprite is red, the color changes to blue as the red 1PN2 emissions are quenched at lower altitudes. Also contributing to the lower altitude blue emissions are nitrogen ion emissions created in the downward propagating streamer heads.

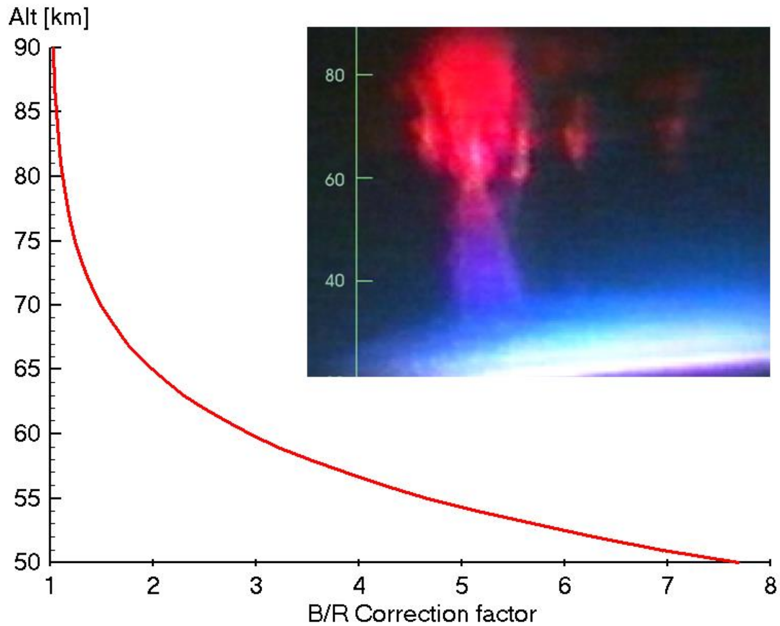

Figure 2. Quenching factor of the blue/red, 2PN2/1PN2, emission ratio based on the MSIS-E-90 model atmosphere with emission and quenching rates from Ihaddadene and Celestin (2016). The inserted color image is from Sentman et al. (1995) recorded with a University of Alaska color TV camera. It illustrates the effect of quenching. The pronounced blue bottom of the sprite is mainly due to atmospheric quenching of the red 1PN2 emissions.

4.3. Blue and Red emissions

The examples of the 4 sprite features (downward and upward propagating streamers, glow, and beads) shown in Figure 1 show that blue emissions, indicating a more energetic process, are mainly prominent in streamers. This is generally true for the entire data set analyzed. To analyze the differences more quantitatively we extracted from each spectrum the ratio between the blue emissions (380-450 nm) and red emissions (625-700 nm). Then to establish a characteristic B/R ratio for each of the 50 time series we averaged the ratios within each time series. Then we averaged the averages within each of the 4 sprite features, downward and upward propagating streamers, glows, and beads. Because of the uncertainty on the quenching correction introduced by the assumption of the sprite features located at the same range as the causal lightning strike, we give the statistics for both the observed B/R ratios and the quenching corrected values. The ratios are not corrected for instrument response or atmospheric effects. A summary of the data is given in Table 1.

	Downward streamer	Upward streamer	Glow	Bead
Number of time-series	18	6	12	14
Number of spectra in each	4-21	3-11	5-70	4-77
Observed B/R ratio range	0.058-0.300	0.018-0.164	0.004-0.114	0.000-0.053
Average obs. B/R ratio	0.178	0.077	0.034	0.013
Corrected B/R ratio range	0.010-0.179	0.013-0.092	0.003-0.051	0.000-0.020
Average corr. B/R ratio	0.055	0.047	0.017	0.006
Median corrected B/R ratio	0.050	0.057	0.013	0.006

Table 1. Summary of data set. Line 1: Number of time-series in each of the 4 sprite features. Line 2: Range of the number of spectra in each sequence, e.g. the number of spectra in the 18 downward streamer sequences vary from 4 to 21. Line 3: Range of averaged ratios within each of the 4 sprite features. Line 4: Average of the entries in line 3. Line 5 has the quenching corrected ratio ranges and line 6 the corresponding averages. Last line, line 6, has the median of the quenching corrected averages.

The summary confirms that the blue emissions are primarily associated with streamers. The average quenching corrected B/R ratios for downward propagating streamers is larger than the ratio for upward propagating streamers, as would be expected from models (e.g. Babaeva and Naidis, 1997; Liu and Pasko, 2004; Luque et al., 2008; Qin and Pasko, 2014), but the difference is small and well within the uncertainty on the analysis. The B/R ratios for glow and beads are low. In several of the bead time series analyzed there were no blue emissions detected. Also, in contrast to the streamers, glow and beads are essentially stationary and longer lasting, and consequently, their time series are generally significantly longer.

The largest quenching correction to the observed B/R ratios is for downward streamers. This is not surprising since downward streamers generally propagate to altitudes lower than upward streamers, glow, and beads. With the quenching correction we find the average ratio of downward streamers slightly larger than that of upward streamers in qualitative agreement with streamer models. We tried different assumptions for deriving the altitudes to see the impact on the quenching corrected emission ratios. Pasko and Stenbaek-Nielsen (2002) suggested that the change to very diffuse emissions often seen in the top of carrot sprites around 80 km altitude is associated with a sharp increase in conductivity at the edge of the ionosphere. This morphological boundary is very easy to identify when present. Another method is to set the altitude for a given sprite feature, and then adjust the range accordingly. The different assumptions significantly affects the ratios in individual spectral time series, but surprisingly, the average quenching corrected B/R ratio for downward streamers remains slightly higher than that for the upward streamers. Nevertheless, the uncertainty on the ratios remains substantial.

4.4. Temporal variations in blue and red emissions

The statistical analysis presented in the previous section showed the more energetic nature of streamers relative to glow and beads. We now turn to an evaluation of individual spectral time series to extract information about general systematic temporal changes in the spectra from each of the 4 small scale sprite features considered.

Temporal changes in the blue to red ratio may indicate a change in the electron energies leading to the emissions. The blue to red ratio is affected by quenching which is altitude dependent reflecting the exponentially increasing atmospheric density with lower altitude (Figure 2). The effect is particularly important in downward streamers as they can propagate through several scale heights. We corrected the ratios for quenching by assuming that the range to the emitting sprite feature is the same as to the causal lightning strike reported by NLDN recognizing, as described in sections 4.1 and 4.2 above, the significant uncertainty associated with this assumption. The quenching correction will remove ratio changes within individual time series solely due to the changing altitude. If a different range is used the altitudes of all data points within the time series will change to higher or lower altitudes obviously affecting the quenching correction, but any temporal changes to the ratios within the individual time series due to processes other than quenching will remain. Thus relative changes in the quenching corrected ratios may indicate a change in the energy of the electrons responsible for the emissions.

The sprite shown in the lower right panel of Figure 1 provided spectral time series for a downward streamer, glow, and two beads, and we show data from this event in Figure 3. The sprite has been discussed earlier by Kanmae et al. (2010b) and by Stenbaek-Nielsen et al. (2013). It is a small and not very bright carrot recorded on 27 August 2009 at 09:15:23 UT over Oklahoma in the US Mid-West. The event has Jupiter in the field of view and we use the standard deviation observed in the Jupiter spectra (see section 3 above) to estimate error bars on the spectral ratios derived.

The top panel of Figure 3 has a series of 50 tall and narrow image strips, 5 ms of time, extracted from the original images to illustrate the morphology. The image used in Figure 1 is at 4.2 ms in Figure 3. The altitude scale is on the left and the elevation angle scale on the right. Luminosity from the causal lightning strike was observed 1.0 ms (10 frames) before the start of the strip image time series plot, and we use that for timing. An elve propagated down across the field of view following the lightning strike, and a sprite halo appeared in the high speed images 0.3 ms after the lightning strike. The panel starts with the first indication of a local intensification within the halo eventually leading to streamer formation at 2.0 ms.

The sprite has usable spectra for the downward propagating streamer dominating the left part of the panel, the associated glow in the top half of the panel, and the two well-defined beads below the glow. The assumed altitudes of the spectra of the streamer and glow are shown in the middle panel, and the quenching corrected blue/red ratios are shown in the bottom panel. We have not plotted data points for the beads since their altitudes do not vary and essentially no blue emissions are present in the bead spectra.

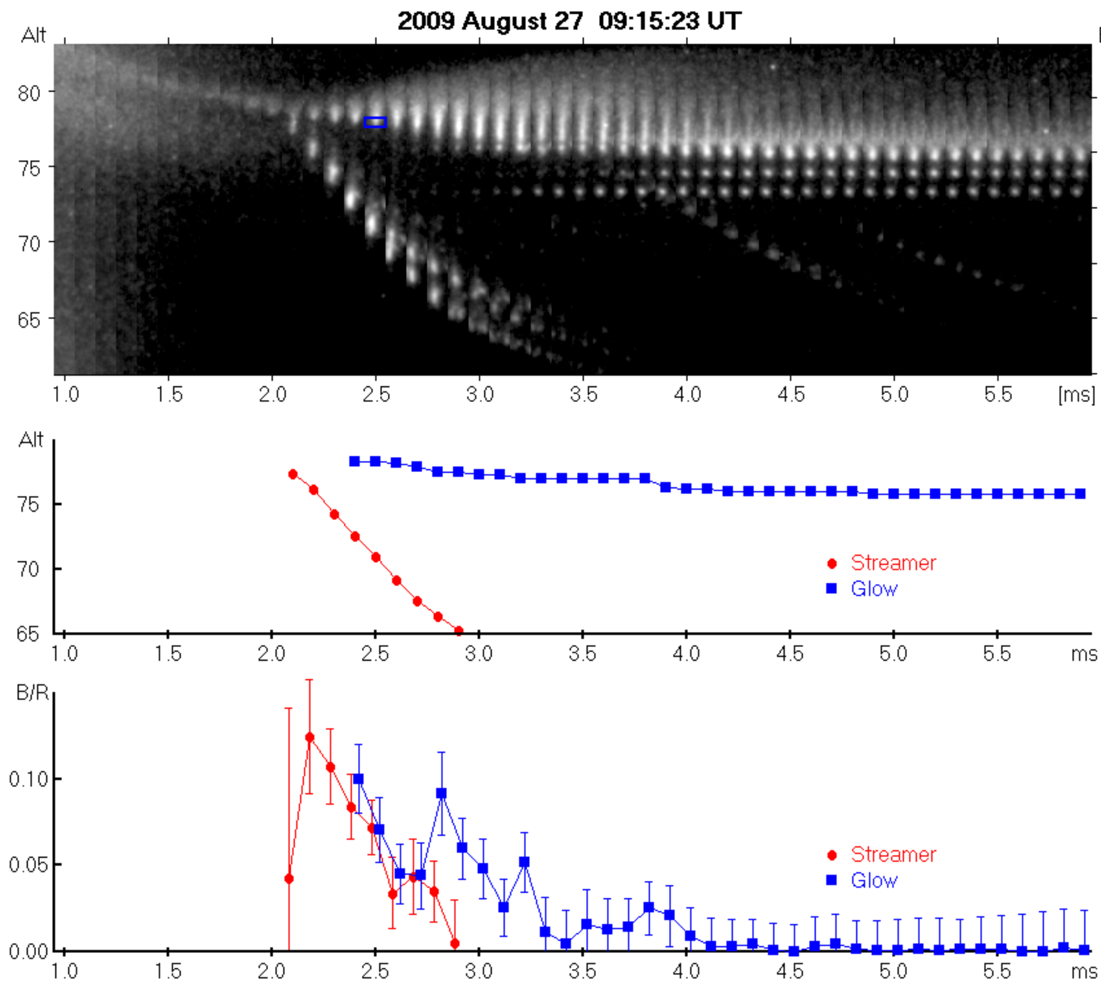

Figure 3. Sprite observed 27 August 2009 at 09:15:23 UT over Oklahoma. The top panel has an image time series starting with the first indication of an intensification leading to streamer formation. The image time series has several streamers, glow and beads. Spectra of the dominant streamer and the glow above were extracted from a narrow altitude range (range for the glow is indicated with a blue box at 2.5 ms). The middle panel shows the altitudes the streamer (in red) and the glow (in blue). The bottom panel has the quenching corrected blue to red emission ratios derived from the observed spectra with associated error bars. The time axis is ms from the lightning/elve associated with the sprite. The data points for the streamer and glow ratios have been slightly offset to avoid overlapping error bars.

At start of the image time series an intensification in the halo is seen moving slowly down at 0.3 10^7 m/s leading to streamer initiation around 2.1 ms. The spectra for the intensification are very noisy, but there are no obvious blue emissions attributable to the intensification. At the start of the downward propagating streamer blue emissions appear and there is a rapid increase in both streamer brightness and in the blue/red ratio consistent with modeling by Liu et al. (2009b). The maximum streamer brightness is near 2.5 ms at which time a split is observed. The downward velocity of the streamer is initially 1.7 10^7 m/s, but starts to decrease shortly after the split. The blue/red ratio also decreases rapidly as the streamer propagates down. The end of usable streamer spectra is at 2.9 ms, but the streamer is clearly visible beyond that time. It slows down and fades near the bottom of the field of view.

Bright, stationary glow and beads form after streamer onset near the altitude of the onset. In the strip image time series the glow appears as a continuation of the intensification in the halo leading to the streamer initiation. The glow spectra plotted start 2 frames from the streamer onset and the entire glow spectral time series has 80 data points. This is 4.5 ms beyond the time covered in Figure 3. The glow expands both up and down and the spectra are from the lower tip of the glow which is the best defined small feature in the glow. The location at 2.5 ms is shown with a blue box on the strip image in Figure 3 (top panel). There is a faint bead early in the time series at an altitude of 76 km; it brightens as the glow expands down over the bead (which causes the small 'jump' in the altitude of the spectra at 3.8 ms). We see this development quite often in our high speed sprite recordings although in this case the bead remains distinct to the end of the time series.

The blue/red ratio for the glow is initially similar to that for the streamer, and it decreases as the streamer fades. There is a slight increase in the ratio starting around 3.5 ms, which is likely associated with additional streamer activity. For most of the glow, from 3.0 ms until the end of the time series at 9.3 ms, very little blue is detected. This is quite representative of our data; when blue emissions are present, they appear to be associated with streamer activity early in the sprite event.

Below the glow there are two well defined beads which formed in the streamer channel some tenths of milliseconds after the streamer passage. This is very typical of sprite bead formation (Luque et al., 2016, Stenbaek-Nielsen et al., 2013). As mentioned above we do not show the data for the beads in the lower panels of Figure 3 since there are essentially no blue emissions detected.

The downward propagating streamer in Figure 3 fades near the bottom of the field of view, but there are no usable spectra covering the fade. However, we do have spectra covering the fade of another downward propagating streamer in the same event. The streamer enters the field of view from above slightly left of the streamer in Figure 3 and 0.1 ms earlier. Data for this streamer is presented in Figure 4 using the same format as for Figure 3. Initially there are significant blue emissions, but towards the end, as the streamer fades, the blue/red ratio decreases to near zero. We see that too in other time series covering streamer fade. We do not plot the estimated error for the last three data points; the streamer is here very faint and error estimation becomes meaningless.

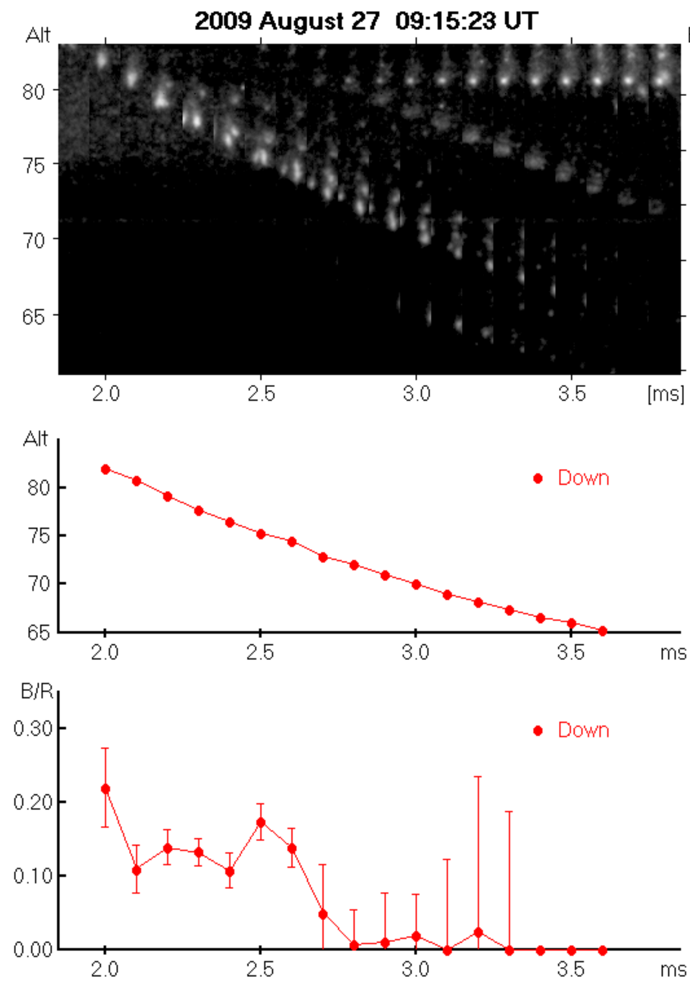

Figure 4. Sprite observed 27 August 2009 at 09:15:23 UT over Oklahoma (from the same event as shown in Figure 3). The top panel has an image time series starting at the time the streamer comes into view. The middle panel shows the altitude of the streamer and the bottom panel has the corresponding quenching corrected blue to red emission ratios derived from the spectra. The time axis is ms from the lightning/elve associated with the sprite.

The initial ratios in the streamer are higher than those shown in Figure 3, but this is very likely an artifact of the assumption that all features in the images are at the same range. The streamer initiates in the halo as did the streamer in Figure 3, but it is higher in the Phantom field of view indicating a higher altitude which leads to a smaller quenching correction. A more likely interpretation is that the streamer originates closer to the aircraft and therefore higher in the field of view, but not higher in altitude. If we set the range so the onset altitude is the same as used for the streamer in Figure 3, the blue/red ratios will be similar to the values shown in Figure 3.

Our data set has 18 time series of downward propagating streamers with 12 spectral time series covering streamer onset and most, 8 of the 12, have onset against a dark sky. For these streamers, in contrast to the streamer shown in Figure 3, the streamer brightness and downward velocity increases gradually. An example is shown in Figure 5 using the same format as Figure 3. This sprite was observed on 19 August, 2009, at 05:37:36 UT west of Oklahoma City. We do not have any indication of the causal lightning strike in the high speed images (luminosity from the strike or an elve). NLDN does report the strike, but only with 100 ms time resolution, so we use the first indication of the downward propagating streamer for timing. The event has no stars present that can be used to estimate the error on and confidence in the derived blue/red ratios, but the instrument settings are similar and we use the Jupiter spectra used for the event in Figures 3 and 4.

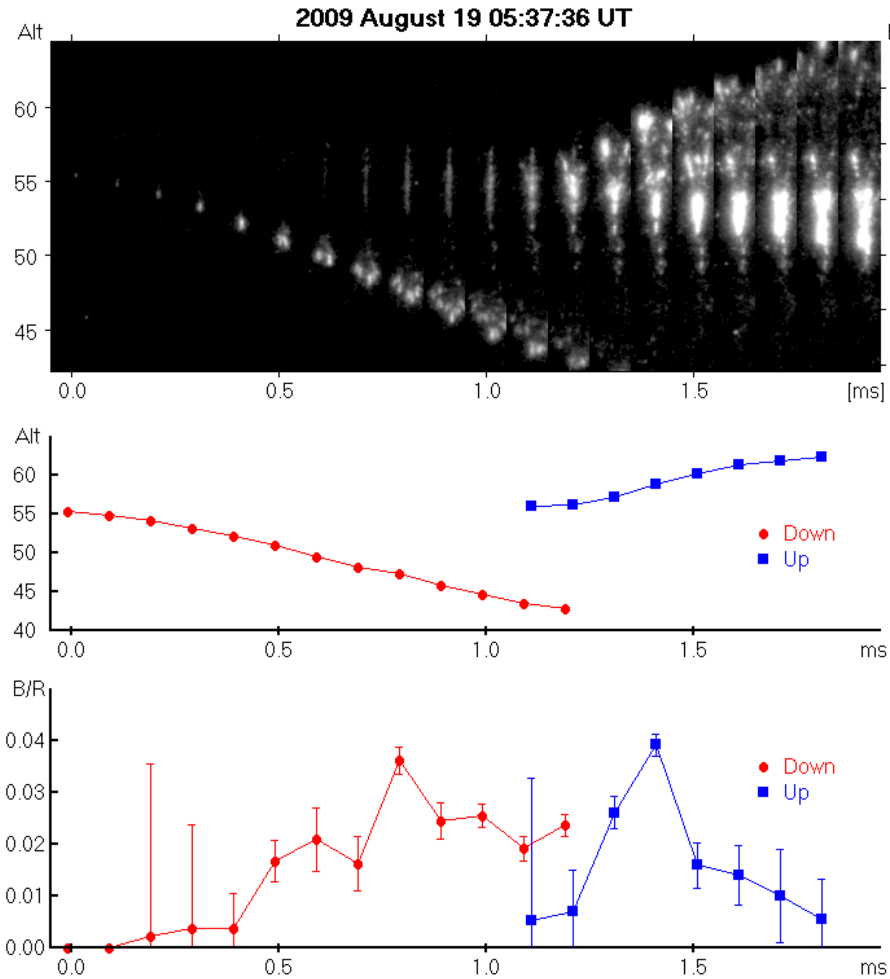

Figure 5. Sprite observed on 2009 August 19 at 05:37:36 UT over Western Oklahoma. The top panel has 20 narrow strips extracted from the Phantom images. The image time series shows the development of a downward propagating streamer with onset against a dark sky followed by an upward propagating streamer. The center panel has the altitudes of the downward propagating streamer in red and the upward propagating streamer in blue. The bottom panel shows the corresponding blue/red ratios derived from the observed spectra. The data points for the blue/red ratios have been slightly offset to avoid overlapping error bars at 1.1 ms.

The streamer is initially very faint and the first two data points are included to illustrate the gradual brightness and velocity increase of the streamer. No blue emissions were detected and because of the low brightness we do not estimate the error. As the streamer brightens the downward velocity increases gradually from 0.5 10^7 m/s at onset to a maximum of 1.5 10^7 m/s. The blue/red ratio is low at onset, but increases after 4 frames. The streamer never becomes very bright, and it exits the imager field of view at 1.3 ms.

The event in Figure 5 also has an example of an upward propagating streamer with usable spectra. This is one of 6 in the total data set. The sequences of upward streamers generally consist of fewer frames, and the red and blue spectral features used for the analysis are often poorly defined because of the presence of other activity nearby. Essentially, well-defined spectra are recorded only for streamers propagating up above the glow and activity in the onset region as in the example in Figure 1. Our best example is the one shown in figure 5. At streamer onset and towards the end there is less light detected in the blue. The first detection of the upward streamer is at 0.8 ms, but spectra are only usable from 1.1 ms. There are splits in the streamer, and this example does not end with a diffuse cloud at the top as is most often observed. The maximum upward velocity is 1.7 10^7 m/s slightly higher than the maximum velocity, 1.5 10^7 m/s, in the downward streamer in the figure consistent with earlier analysis results by McHarg et al. (2007), Li and Cummer (2009), and Stenbaek-Nielsen et al. (2013).

5 Discussion

The ratio of the molecular nitrogen emissions in the blue (2PN2) to the red emissions (1PN2) with appropriate corrections for instrument response, quenching, and atmospheric absorption were originally intended to be used to verify sprite model results. However, as discussed in this paper, the assumption of the sprite located at the same range as the causal lightning strike introduces significant uncertainty on the derived altitudes, and therefore on the quenching correction. To illustrate this we may look at the spectra from the downward and upward propagating streamers shown in the top row of Figure 1. The two spectra are from the same event observed over southern Nebraska on 2 August 2013 at 06:57:20 UT. The observed blue to red ratio for the downward streamer (Figure 1 top left) is 0.36 and 0.13 for the upward streamer (Figure 1 top right). The corresponding altitudes, assuming the same range as the causal lightning strike, are 56.2 and 83.3 km, and correcting for quenching (Figure 2) the ratios become 0.09 and 0.12. This would indicate the upward streamer to be more energetic than the downward streamer, in conflict with modeling by Liu and Pasko (2004) and Liu et al. (2014). If the range is increased by for example 40 km, the mean distance between the sprite and the causal lightning strike reported by Sao Sabbas et al., (2003), the altitudes for the two features would increase leading to quenching corrected ratios of 0.14 and 0.12; the downward streamer is now the more energetic.

The large uncertainty clearly shows the need for better sprite altitude determination. An obvious solution is to have multiple stations so the sprite altitudes can be derived by triangulation. Another possibility would be to avoid using the 1PN2 band emissions which are most affected by quenching. Modeling by Pérez-Invernón et al. (2018) indicate that the ratio of 2PN2 to 1NN2+ can be used, but these optical bands are both in the blue and may be difficult to separate in slit-less spectroscopic data. This problem can be overcome by adding narrow band filtered imagers to augment the spectral images. Observations using multiple imagers with narrow band optical filters were used in some of the early aircraft observations (Morrill et al., 2002; Armstrong et al., 2000) and is used in current observations from the International Space Station (Neubert et al., 2019).

While the blue to red nitrogen emission ratios derived are associated with large uncertainties, we note that just the presence of blue emissions will indicate a more energetic process. The analysis presented here shows that blue emissions are primarily associated with streamer processes early in a sprite event. This supports the suggestion made in the early years of sprite research by Suszcynsky et al. (1998) and Armstrong et al. (2000) that there are two separate mechanisms associated with the sprite emissions: An initial energetic process, which we here identify as associated with streamer activity, followed by less energetic processes associated with the much longer lasting glow and bead sprite features.

Analysis of the streamer spectra shows temporal changes in the blue to red emissions ratios within individual time series indicating corresponding changes in the energy of the electrons leading to the emissions. The data set has 18 time series of downward propagating streamers with 12 covering streamer onset. Of the 12, 4 have onset in or near a sprite halo and 8 have onset against a dark sky.

The 4 time series with onset in or near a sprite halo are prompt sprites with streamer onset within a few ms of the causal lightning strike. The streamer brightness and velocity increases very rapidly, and they emerge from the halo with blue to red ratio and downward velocity near the maximum observed for that individual streamer. The maximum downward velocity in the 4 streamers is in the range 1.5-2.5 10^7 m/s. An example was presented above in Figure 3.

The 8 streamers with onset against a dark sky are all delayed sprites with onset 50-300 ms after the lightning strike. In contrast to the rapid brightening and high initial downward velocity observed in the prompt streamers, the brightness and downward velocity increase gradually, typically over about 0.5 ms (5 frames). An example was presented in Figure 5 above. Similar examples (but without spectral information) may also be found in Stenbaek-Nielsen et al. (2010). The maximum downward velocity in the 8 streamers is in the range 1.0-2.0 10^7 m/s, slightly less than the downward velocity range for the prompt streamers. The delayed sprites appear to have their onset at a lower altitude than the prompt sprites as has been reported by Li et al. (2008) who quote a 5 km altitude difference.

Towards the end of the downward propagation the streamer gradually fades. The streamer fade is covered in 8 of the 18 time series. The fade is often associated with a decrease in downward velocity, but the decrease varies considerably between events and does not appear to be obviously associated with the decrease in streamer brightness. An example was presented in Figure 4. Li and Cummer (2012) found that the streamers begin their significant deceleration where the background field drops below 12–24 % of the local electric break-down field, E_k, and that the fade is at the altitude where the ambient E field is 5% of E_k.

The spectra of the upward propagating streamers appear to follow the same development with little blue emissions at the start and end of the streamers (Figure 5). However, our data set for upward streamers is very limited.

In sprite glow and especially in beads we find little or no blue emissions. Most of the blue emissions in glow are observed early when streamer activity is present. However, we do have examples where the blue emissions extend beyond the end of streamer activity, as determined from the high-speed images. This may indicate that the emissions may not be entirely from streamers within the region of the glow, and we suggest that they may be associated with currents in the streamer channels as first proposed by Lui (2010) and later by Luque et al. (2016).

Luque et al. (2016) showed that glow and beads in the same streamer channel decay with the same time constant even though they were several scale heights apart in altitude indicating a coupling of the processes within the channel. They suggested a model in which the emissions in the glow and beads are produced by the same process driven by the current in the channel. The local E-field in the channel is dictated by the current which through an electron attachment instability drives the local plasma in the channel into one of two states: a high conductivity state resulting in a low E-field and no optical emissions, or, a low conductivity state resulting in a high E-field and optical emissions which would be the channel glow and beads. The E-field in this model is naturally limited to the local field required for ionization, E_k; if the field locally increases above E_k ionization would occur increasing the conductivity and consequently, with the current being constant the local E-field in the channel would decrease. As the sprite decays the current decreases and the E-field would decrease as well. Eventually there will be only 1P emissions present. As the current decay further there will be no optical emissions, but the channel will remain providing a seed for sprite re-ignition as is often observed (Stenbaek-Nielsen et al., 2000; 2013; Sentman et al., 2008).

Acknowledgments

We gratefully acknowledge the support of the NSF/NCAR High Performance Instrumented Airborne Platform for Environmental Research (HIAPER) project, as well as the pilots and technical staff that made the HIAPER Gulfstream V missions possible. We also acknowledge the contribution by T. Kanmae who did the early analysis of the spectra, and discussions with N. Liu, F. J. Pérez-Invernón, and A. Malagón-Romero. The data presented here are available on Open Science Framework (htpps://osf.io) in project “Sprite Spectra at 10,000 fps”. The data are also available from H. Stenbaek-Nielsen (hcnielsen@alaska.edu) or M.G. McHarg (Matthew.McHarg@usafa.edu). The research has been supported in part by NSF grants 1104441 to the University of Alaska Fairbanks and 1201683 to the US Air Force Academy.

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